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GRAPHITE-FIBER - POLYIMIDE COMPOSITES FOR SPHERICAL BEARINGS TO 340° C (650° F)

by Harold E. Sliney and Robert L. Johnson

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

Journal bearings with self-alining spherical elements of graphite-fiber-reinforced - polyimide composites were tested from 24° to 340° C (75° to 650° F) at unit loads up 3.5×10^{7} N/m^2 (5000 psi). The journal oscillated in the cylindrical bore of the composite element ±15° at 1 hertz. Outer races and journals were metal hardened to Rockwell C-32 and finished to 10^{-7} m (4 μin.) rms. A 45 wt.% graphite-fiber composite gave low friction (0.08 to 0.13), low wear, and almost no plastic deformation under any of the test conditions. Composites with 15 and 25 wt.% graphite fiber failed by plastic deformation at 315° C (600° F) and 3.5×10^{7} N/m^2 (5000 psi). A composite with 60 wt.% graphite fiber failed by brittle fracture under the same conditions, but had very low friction coefficients (0.05 to 0.10) and may be a good bearing material at lighter loads.

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SUMMARY

Spherical bearings were tested from 24° to 340° C (75° to 650° F) at unit loads to 3.5×10^{7} N/m^{2} 5000 psi. The journal oscillated ±15° at a frequency of 1 hertz in the cylindrical bore of a self-alining composite ball or spherical element. The spherical elements of the bearings were molded composites of graphite fiber and an addition-type polyimide resin. (Addition-type polymers undergo the final stages of polymerization without the release of volatile reaction products and were therefore advantageous in the preparation of low porosity composites.) Outer races and journals were age-hardened (Rockwell C-32) super alloys with a surface finish of 10^{-7} m (4 μin.) rms. Composites containing 15, 25, 45, and 60 wt.% chopped graphite fibers 6.4×10^{-3} m (1/4 in.) long by 8.4×10^{-6} m (3.3×10^{-4} in.) equivalent diameter) were studied. The 15 and 25 wt.% graphite composites failed by plastic deformation, then fracture at 315° (600° F) and 3.5×10^{7} N/m^{2} (5000 psi) unit load. The 45 wt.% graphite composite had a bearing load capacity of at least 3.5×10^{7} N/m^{2} (5000 psi) at all temperatures up to 340° C (650° F) and exhibited low torque, low wear, and no significant plastic deformation during the bearing tests. The 60 wt.% composite failed by brittle fracture under the same conditions but had very low friction coefficients (0.05 to 0.10) and may therefore be a suitable bearing material to 340° C (650° F) at lighter loads.

INTRODUCTION

Current operational airframe bearings provide good reliability and low torque at temperatures to 162° C (325° F). PTFE (polytetrafluoroethylene)-lined metallic bearing surfaces are commonly used. The liner is a composite structure with PTFE as the lubricating source which is reinforced to obtain high static and dynamic load capacities.

A common reinforced liner material is a cloth formed of PTFE fibers and fiber of either glass, dacron, or cotton; PTFE-lined bearings have very low friction and require little maintenance during their useful life.

The increased aerodynamic heating of aircraft at Mach 3 or higher can result in control surface temperatures well above the temperature limitations of present airframe bearings. Re-entry vehicles are an extreme case in which aerodynamic heating is encountered. Figure 1 taken from reference 1 shows that, for re-entry vehicles, skin temperatures of 980° C (1800° F) or higher are expected in the vicinity of the control surfaces. Actual bearing temperatures will depend on the degree of cooling, insulation, and ablation protection provided. All of these methods of thermal protection mean added weight and complexity. In order to minimize the weight of the thermal protection system, airframe structural members may be allowed to get as hot as mechanical strength considerations will allow. Creep limitations, for example, dictate a maximum of about

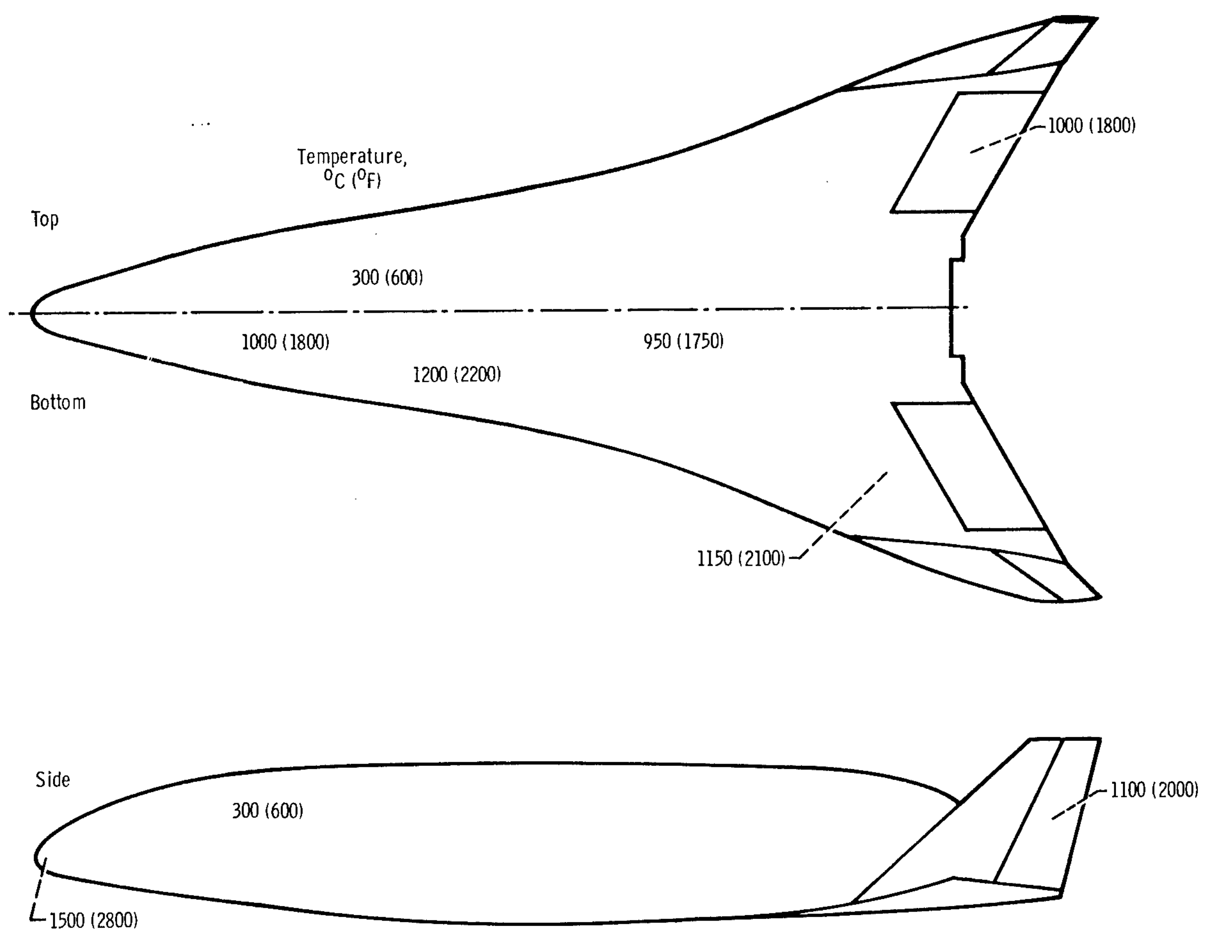


Figure 1. - Approximate temperature distribution for one concept of space shuttle orbiter (ref. 1).

340° C (650° F) for the titanium alloys which are replacing aluminum in some advanced high-speed aircraft. Increased airframe temperatures, therefore, dictate that control surface bearings and other airframe bearings with capabilities well above 162° C (325° F) will be needed.

It has been shown recently that composites consisting of graphite fiber and a high-density polyimide resin retain good mechanical strength for at least 1000 hours at 260° C (500° F) and for over 200 hours at 315° C (600° F) (refs. 2 and 3). Polyimides are known to have good friction and wear characteristics, especially when combined with lubricating fillers such as powdered graphite or MoS_2 (refs. 4 and 5).

The incorporation of high-strength graphite fiber in a polyimide matrix to provide mechanical reinforcement in addition to lowering friction introduces the possibility of using the composite directly as a bearing material for high-load applications.

It was the purpose of our experiments, therefore, to determine the performance of graphite-fiber polyimide as a bearing material for the oscillating plain spherical bearing at temperatures from ambient to 340° C (650° F) and at unit loads to 3.5×10^{7} N/m^{2} (5000 psi). Oscillation was $\pm15^{\circ}$ at 1 hertz. The tests were performed in an air atmosphere with an ambient relative humidity of about 50 percent. The tests were limited in number and were intended to demonstrate feasibility and to approximate an optimum graphite-fiber - resin ratio.

TEST BEARINGS

The design of the test bearings is illustrated in figure 2. The spherical element of the bearing is a molded composite material made of graphite-fiber-reinforced polyimide resin. Variable graphite-resin ratios were evaluated in this program. The graphite used in preparing the composite spherical elements is in the form of chopped fibers 6.4×10^{-3} meter (1/4 in.) long, with an equivalent diameter of 8.4×10^{-6} meter (0.00033 in.) and a specific gravity of 1.4. The polyimide resin is an addition-type polymer. Addition polymers are a type which undergo the final stage of polymerization without releasing volatile reaction products. This type of polymerization is advantageous (compared to the condensation-type polyimides which release water as a byproduct of polymerization) in molding thick sections with low void content.

The outer races are in two pieces and are made of René 41, a precipitation hardening nickel alloy. The journal is Stellite 6B a precipitation hardening cobalt alloy. The alloys were hardened to Rockwell C-32 and the sliding surfaces were ground to a 10^{-7}-meter (4-μin.) rms finish. These alloys were used because they were already available. Less costly, hardenable stainless steel, such as high-temperature modi-

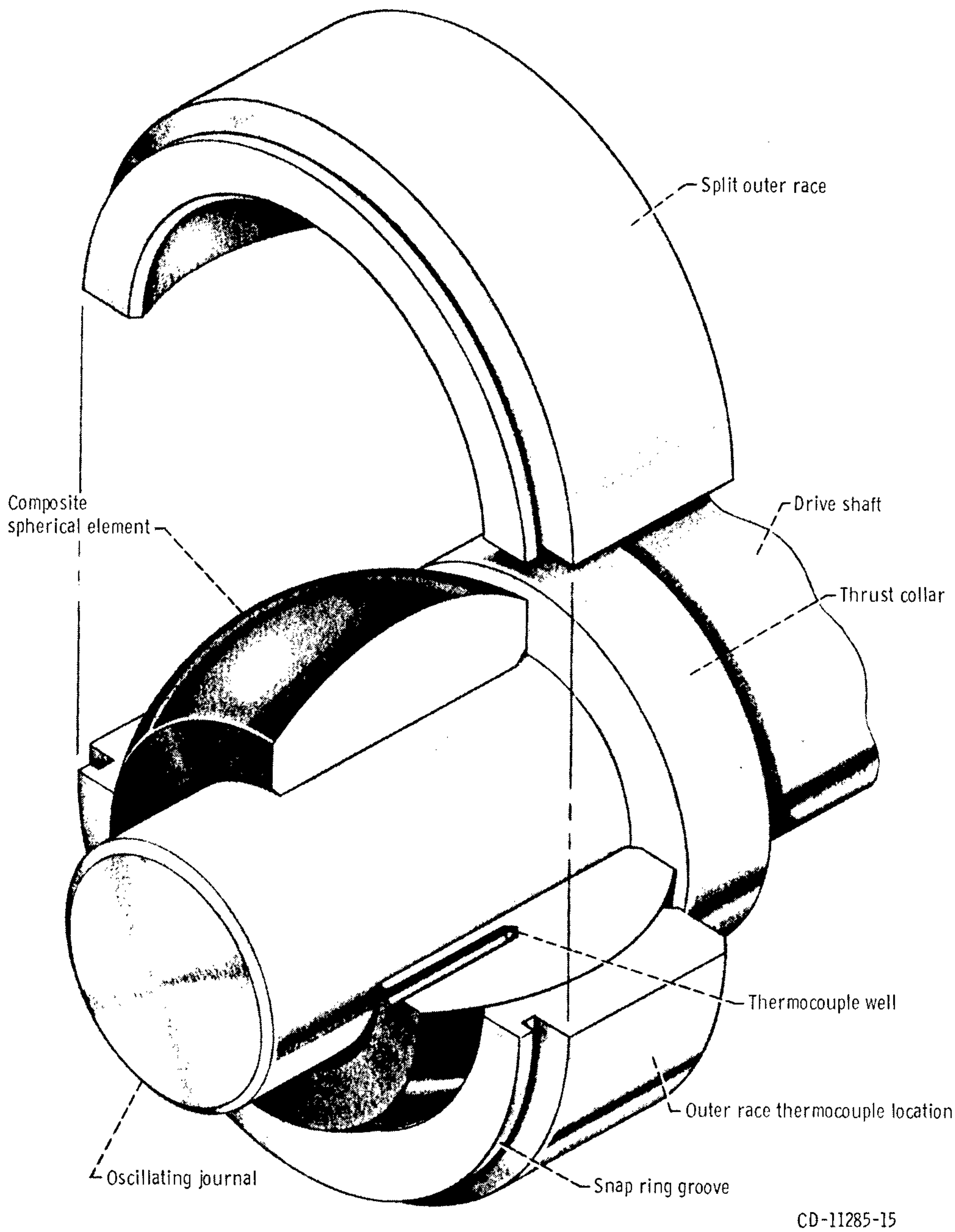


Figure 2. - Spherical test bearing.

fied 440-C, would be harder (R_c 60) and should have adequate strength and oxidation resistance for the 340° C (650° F) maximum bearing test temperatures.

The bearing bore is 1.591×10^{-2} meter (0.6265 in.) in diameter and 1.9×10^{-2} meter (0.75 in.) long. The spherical diameter is 2.923×10^{-2} meter (1.151 in.). Diametral clearances between the journal and the bore and between the spherical element and the outer race are each 3.8×10^{-5} meter (0.0015 in.).

The bearings are mounted for testing with a floating (unclamped) spherical element. Therefore, the journal oscillates in the bearing bore. The primary purpose of the spherical surface is for self-alinement of the bearing. In the event the friction coefficient at the journal surface increases sufficiently, the spherical element is free to oscillate. This redundance can be useful in preventing unexpected bearing seizure and in prolonging bearing life.

BEARING TEST MACHINE

A diagram of the bearing test rig is given in figure 3. The test bearing is mounted into a large nickel alloy plate which acts as a bearing housing and as a susceptor for induction heating of the bearing. This disk is supported by a web of nickel alloy bars which is welded to the disk at one end and to the front flange of the rig at the other end.

The oscillating journal is taper-mounted into a drive shaft which is supported at both ends by roller bearings. Pure radial loading was used in this program but axial loads can be applied in this test machine by means of a hydraulic actuator which presses a large hardened metal ball against the back end of the drive shaft.

The drive shaft housing is trunnioun-mounted. A hydraulic cylinder is used to apply a radial load through a rod attached to the one end of the drive shaft housing. The drive shaft is oscillated by means of a reversible hydraulic actuator. The actuator piston moves at constant velocity over most of the stroke in each direction. The actuator drives the journal in very nearly a constant velocity motion which reverses in direction each half cycle. This motion simulates the motion in an actual aircraft control surface actuator and bearing assembly more closely than the simple harmonic motion provided by a motor-driven crank.

Induction heating is used to heat the test bearing. The induction coil (not shown in fig. 3) is located around the bearing mounting plate. A smaller diameter coil is located around the forward extension of the bearing journal. The bearing is, therefore, heated by conduction from the heated housing and journal.

Suitable feedthrough ports are provided for thermocouple and induction coil leads. Thermocouples are press-mounted against the bearing outer race and in some cases imbedded in the bearing ball (see fig. 2).

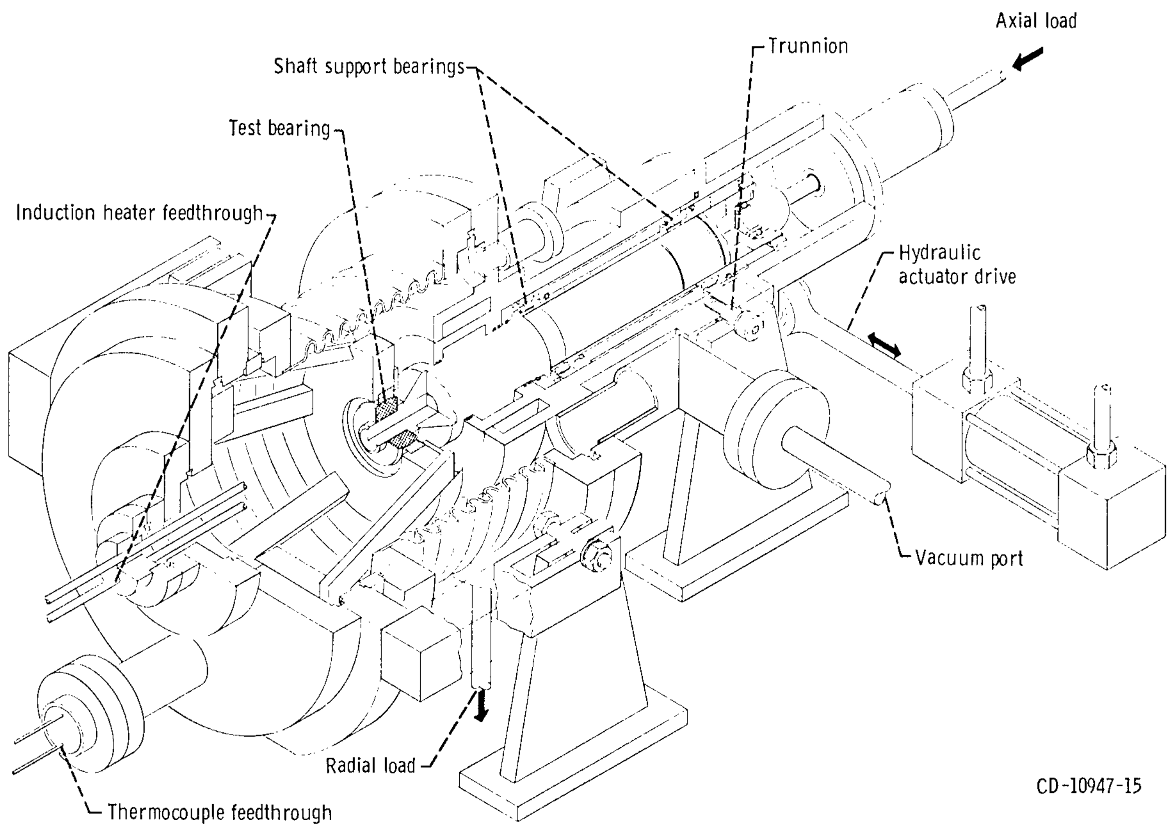


Figure 3. - High-temperature oscillating bearing test rig.

BEARING TEST PROCEDURE

The bearings were first subjected to radial load capacity tests at room temperature and at various elevated temperatures up to 340° C (650° F). Because the journal oscillated in the bearing bore, unit loads were calculated based on the projected area (diameter by length) of the bearing bore. Journal oscillation was $\pm 15^{\circ}$ at 1 hertz. At each temperature the unit load was increased in 7×10^{6} N/m^2 (1000 psi) increments up to a maximum of 3.5×10^{7} N/m^2 (5000 psi). If the bearing did not fail at the maximum test load and temperature, three tests over a simulated re-entry temperature profile were performed. No attempt was made to simulate other re-entry profiles such as load or atmospheric pressure.

The simulated re-entry tests consisted of beginning bearing oscillation at room temperature under a nominal radial load of 13.6 kilograms (30 lb) then increasing the unit load in 7×10^{6} N/m^2 (1000 psi) increments (2 min at each increment) up to the test load of 3.5×10^{7} N/m^2 (5000 psi). The temperature was then increased to 340° C (650° F) over a period of about 20 minutes. The temperature was held at 340° C (650° F) for 10

more minutes, then the bearing was slowly cooled back to about 66° C (150° F) during an additional 90 minutes. (A typical temperature profile is shown in fig. 7). The bearing was oscillated at ±15° and 1 hertz for a total of 7200 oscillating cycles per simulated re-entry temperature profile.

In this study, only the 45 wt.% fiber structure survived the load capacity tests and was subsequently subjected to the simulated re-entry temperature cycles.

RESULTS

Effect of Graphite-Fiber Content on Bearing Properties

15 wt.% graphite-fiber - polyimide resin ball. - The friction-temperature characteristics of this bearing are given in figure 4. Friction coefficients were about 0.2 or

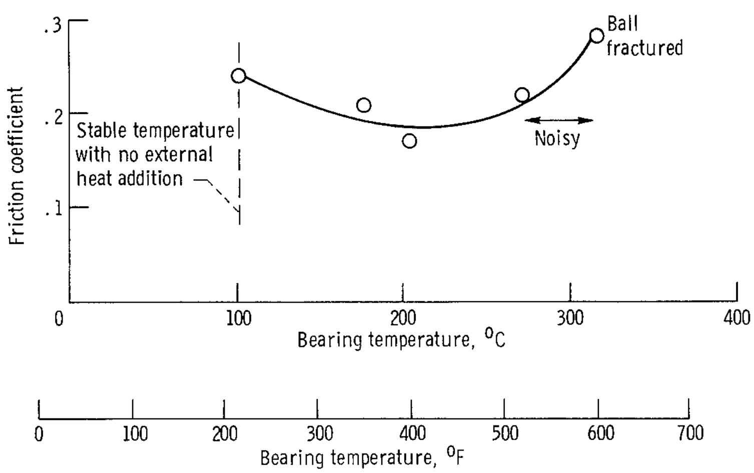


Figure 4. - Friction of spherical bearing with polyimide plus 15 wt.% graphite-fiber composite. Stellite 6B journal; radial unit load, 3.5×10^{7} N/m^2 (5000 psi); journal oscillation in cylindrical bore at 1 hertz, ±15°.

higher at most temperatures from 102° to 315° C (215° to 600° F). The ball fractured at 315° C (600° F) under a radial unit load of 3.5×10^{7} N/m^2 (5000 psi). During room temperature operation at 3.5×10^{7} N/m^2 (5000 psi) unit load, frictional heating alone resulted in an equilibrium ball temperature of 102° C (215° F).

25 wt.% graphite-fiber - polyimide ball. - Figure 5 shows that increasing the fiber content to 25 wt.% significantly reduced the friction of the bearing. The friction coefficient was nearly constant at 0.12 from 60° to 315° C (140° to 600° F). This composite also cracked at 315° C (600° F) under a radial unit load of 3.5×10^{7} N/m^2

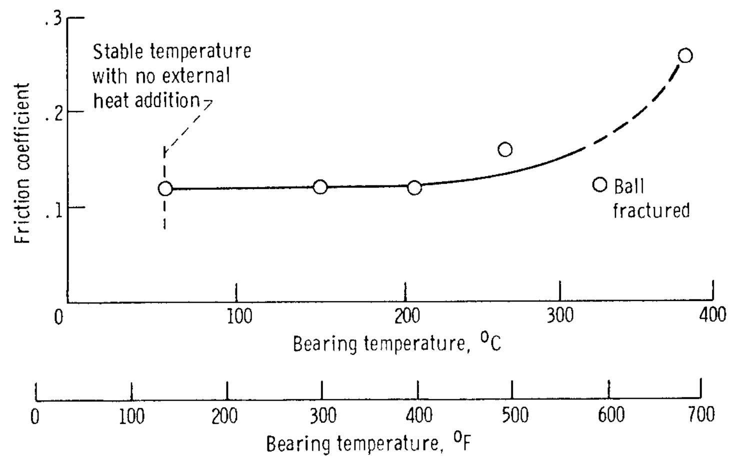


Figure 5. - Friction of spherical bearing with polyimide plus 25 wt.% graphite-fiber composite. Stellite 6B journal; radial unit load, 3.5×10^7 N/m^2 (5000 psi); journal oscillation in cylindrical bore at 1 hertz, $\pm 15^0$.

(5000 psi). However, the bearing was still operable and the test was continued to 340^0 C (650^0 F). Although cracks did not propagate far enough to cause complete fracture of the ball, gross deformation of the bearing bore was observed after the test. The equilibrium temperature of the ball with no external heat addition was 54^0 C (130^0 F). This reduction in equilibrium temperature (compared to the 102^0 C (215^0 F) equilibrium temperature for the 15 wt.% graphite-fiber composite), is a result of the lower frictional heating and the anticipated improved thermal conductivity with increased graphite content.

45 wt.% graphite-fiber - polyimide resin ball. - Figure 6 shows that the friction coefficients with this composite were a little lower than were observed with the 25 wt.%

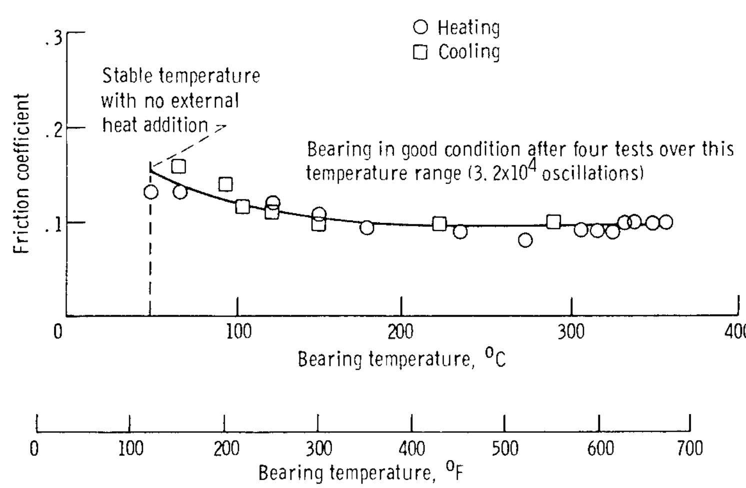


Figure 6. - Friction of spherical bearing with polyimide plus 45 wt.% graphite-fiber composite. Stellite 6B journal; radial unit load, 3.5×10^7 N/m^2 (5000 psi); journal oscillation in cylindrical bore at 1 hertz, $\pm 15^0$.

graphite-fiber material at all temperatures above 79° C (175° F). No failure occurred in the load capacity tests up to a maximum unit load of 3.5×10^{7} N/m^{2} (5000 psi) and a bearing temperature of 357° C (675° F). The bearing was then continuously oscillated under a 3.5×10^{7} N/m^{2} (5000 psi) unit load during cooling to 60° C (140° F). No cracks or significant deformation occurred during this entire test. The bearing was then further run through three simulated re-entry temperature cycles with a maximum temperature of 340° C (650° F) and at a constant unit load of 3.5×10^{7} N/m^{2} (5000 psi).

An example of the temperature and friction time profiles during these tests is given in figure 7. (The 340° C (650° F) temperature is the maximum anticipated re-entry

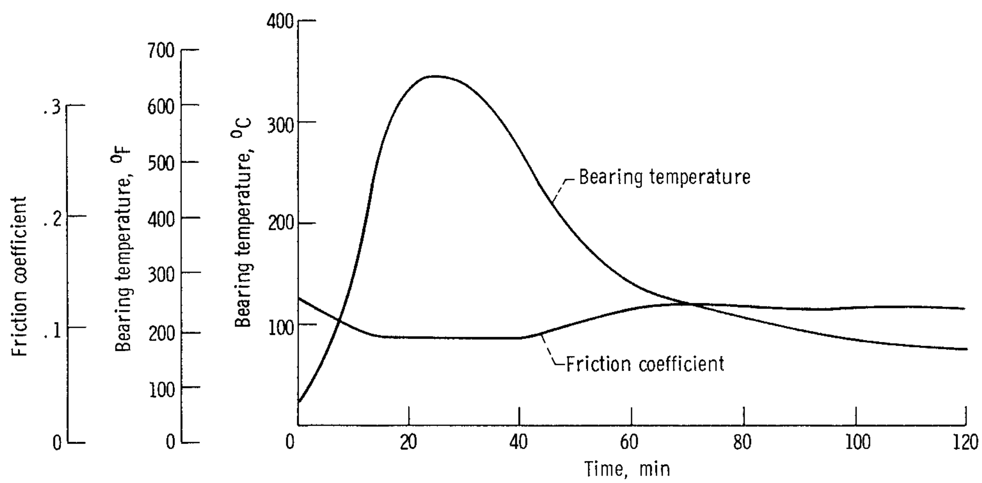


Figure 7. - Temperature and friction profile of bearing with 45 wt.% graphite-fiber-reinforced - polyimide composite during simulated re-entry test.

temperature for a titanium airframe with an insulator/ablator thermal protection system.)

A total of 32 000 oscillating cycles was accumulated during the four tests of this bearing. Only slight deformation and no fracture occurred. No journal wear occurred and a thin film of lubricating material was transferred to the load bearing surface of the journal. The bore of the composite ball developed an eccentricity of 7.6×10^{-5} meter (0.003 in.) due to wear or deformation of the load bearing surface of the bore. The equilibrium temperature of the ball under conditions of no external heat addition was 49° C (120° F).

60 wt.% graphite-fiber - polyimide resin ball. - This material had excellent frictional characteristics to 315° C (600° F) (fig. 8). No plastic deformation was observed but the ball fractured at 315° C (600° F) under a 3.5×10^{7} N/m^{2} (5000 psi) unit radial load. Equilibrium temperature with no external heat addition was only 43° C (110° F)

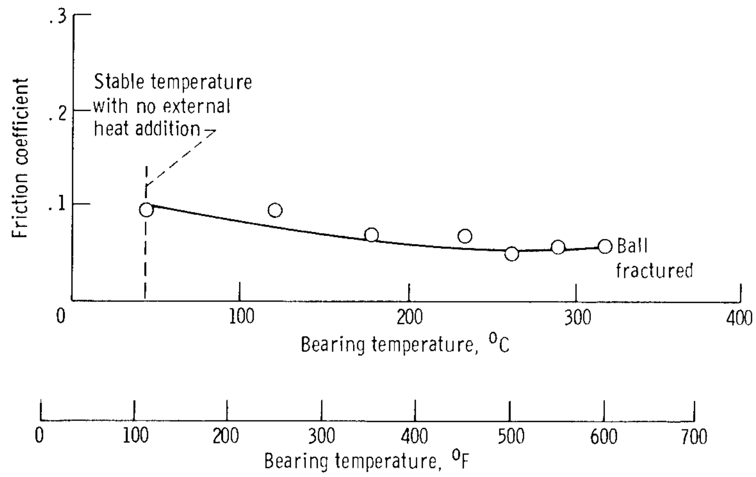


Figure 8. - Friction of spherical bearing with polyimide plus 60 wt.% graphite-fiber composite. Stellite 6B journal; radial unit load, 3.5×10^7 N/m^2 (5000 psi); journal oscillation in cylindrical bore at 1 hertz, ±15°.

because of low frictional heating and good thermal conductivity of this graphite-rich composite.

DISCUSSION

The friction temperature characteristics of all four graphite-polyimide compositions are summarized and compared to the results for a standard (MS 21233-10) PTFE-lined airframe bearing in figure 9. The friction coefficients of the polyimide composites decreased in a regular manner with increasing graphite content. The standard PTFE-lined bearing had very low friction to 204° C (400° F) but the PTFE liner extruded out of the bearing at 232° C (450° F). The maximum service temperature recommended by the manufacturer for the PTFE-lined bearing is 163° C (325° F).

In table I, deformation and wear in the bore of the composite spherical elements and their film-forming characteristics on the journal are summarized. The 15 and 25 wt.% graphite-fiber composites underwent gross plastic deformation then fractured at 315° C (600° F) and a 3.5×10^7 N/m^2 (5000 psi) unit load. However, the 45 wt.% graphite-fiber composite did not fail in the load capacity tests up to the maximum test condition of 3.5×10^7 N/m^2 (5000 psi) unit load at 340° C (650° F) and for a short duration at 357° C (675° F). This composite also performed well in three subsequent re-entry temperature profile tests. The maximum increase in bore diameter (parallel to the radial load direction) was only 7.6×10^{-5} meter (0.003 in.) after 32 000 journal oscillations or less then one-tenth the increase obtained for the lower graphite control bearings after only 4000 or 5000 journal oscillations. The 45 wt.% graphite-fiber composite also formed a

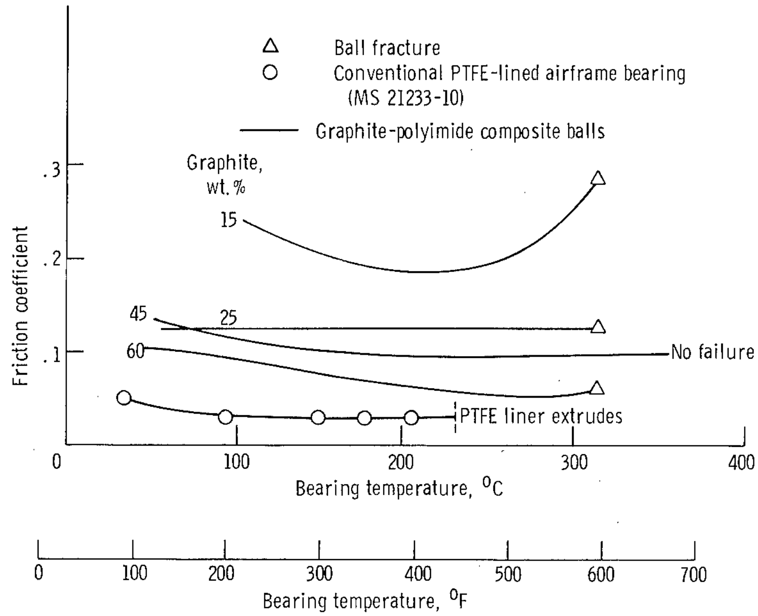


Figure 9. - Summary of friction of spherical bearings with polyimide - graphite-fiber composites of various fiber contents. Stellite 6B journal; radial unit load, 3.5×10^7 N/m^2 (5000 psi); journal oscillation in cylindrical bore at 1 hertz, ±15°.

TABLE I. - BORE WEAR AND DEFORMATION IN GRAPHITE-FIBER - POLYIMIDE SPHERICAL BEARING ELEMENTS

[Oscillation at 1 Hz, ±15°; unit loads to 3.5×10^7 N/m^2 (5000 psi); maximum variable temperature, ambient to 340° C (650° F).]

Graphite content, wt.%	Total journal oscillations, kc	Increase in bore diameter				Appearance of transfer film on journal
		Parallel to load		90° to load		
		mm	in.	mm	in.	
15	5	1.99	0.0785	0.667	0.0263	Powdery, nonadherent
25	4	1.22	.0478	.089	.0035	Thick, patchy adherent
45	32	.076	.0030	.041	.0016	Complete coverage with thin adherent film
60	11	(a)	(a)	(a)	(a)	Barely visible incomplete film

[a]Fracture too extensive to allow accurate measurements.

very thin, uniform transfer film on the journal surface. This type of film is generally observed with plastic-metal sliding combinations that provide low friction and wear. The composites with 15 wt.% graphite content transfered nonadherent, powdery material while the 25 wt.% composite deposited a thick discontinuous film on the journal.

The 60 wt.% graphite-fiber composite failed by brittle fracture at 315° C (600° F) and a 3.5×10^{7}-N/m^{2} (5000-psi) load. This composite transferred a thin adherent film, but it was barely visible and appeared to be discontinuous. Nevertheless, this composite exhibited the lowest friction coefficient of all the graphite-polyimide composites tested; therefore, it may be desirable where minimum friction is needed but load carrying requirements are modest.

The influence of fiber content on the microstructures of the composites is shown in figure 10. The 15 wt.% fiber structure contains randomly scattered, discrete fibers. There is very little continuity or contact among fibers. The 25 wt.% fiber structure begins to show considerable fiber continuity. Nevertheless, this composite experienced considerable deformation in the bearing tests.

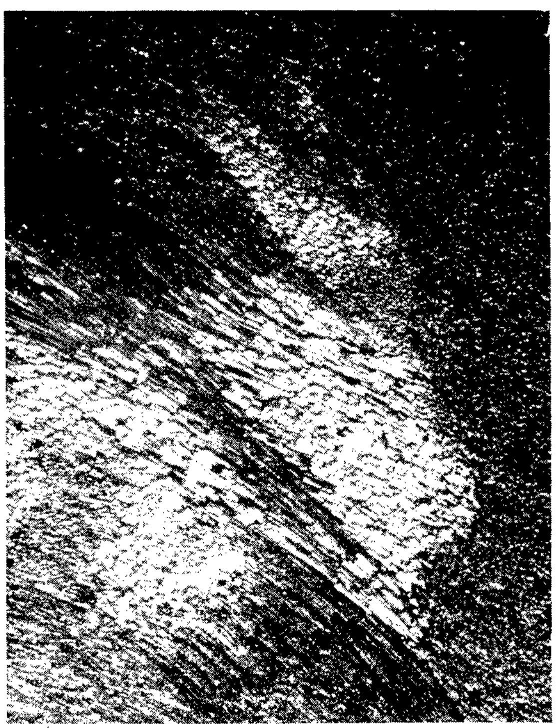
The 45 wt.% graphite structure shows a high degree of fiber saturation. The lower magnification view shows areas of very contrasted reflectivity. Each level of reflectivity represents a different orientation of fiber bundles. The bundles which are parallel to the surface are very reflective (light areas) while the perpendicular bundles are dark. This structure gave the best results with no fracture and only small (7.6×10^{-5} m or 0.003 in.) deformation. The 60 wt.% fiber structure is almost indistinguishable from the 45 wt.% structure but was very difficult to prepare free of resin-deficient areas in the structure.

Graphite additions to polyimide substantially improve thermal conductivity. This is, of course, important for the dissipation of frictional heat from the sliding surfaces. Data (refs. 6, 7, and 8) for the thermal conductivities of graphite and of polyimides with powdered graphite fillers are plotted in figure 11 as a function of wt.% graphite content. Thermal conductivity increases linearly from 0.04 to 0.40 J/(sec)(cm^{2})($^{\circ}$C/cm) from zero to 100 percent graphite. The same trend probably exists for graphite-fiber - polyimide composites; data in figure 11 show that the thermal conductivity of graphite filament is close to that of bulk graphite having a specific gravity of 1.58.

Figure 12 gives data from the bearing tests that are relevant to thermal conductivity considerations. The friction coefficient and the equilibrium temperature rise in the bearing bore caused by frictional heat generation are given for various wt.% of graphite fibers in polyimide. Under conditions of no external heat addition, the temperature rise Δt is directly proportional to the friction coefficient f and inversely proportional to thermal conductivity K; therefore, $\Delta t \propto f/K$ or $K \propto f/\Delta t$. The ratio $f/\Delta t$ is plotted in figure 12 as a function of wt.% graphite fiber. It can be seen that $f/\Delta t$ increases in an approximately linear fashion with graphite content.

(a-1) 15 wt. % graphite.

(a-2) 25 wt. % graphite.



(a-3) 45 wt. % graphite.

(a-4) 60 wt. % graphite.

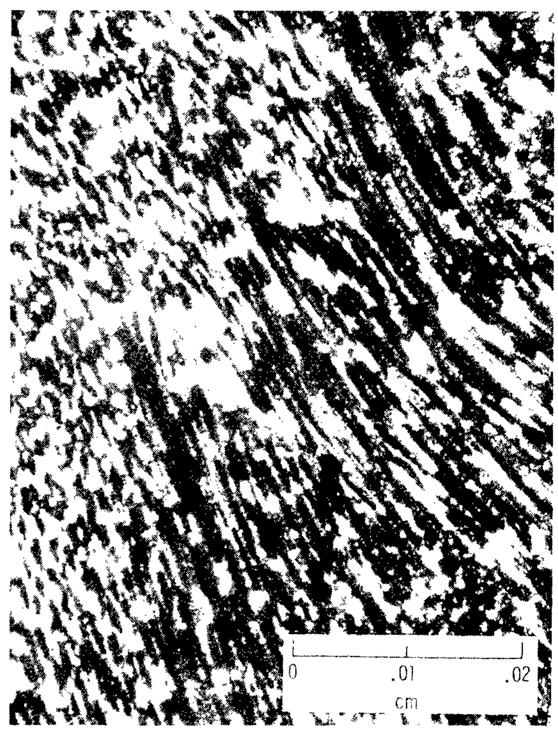
(a) Lower magnification.

Figure 10. - Microstructure of graphite-fiber - polyimide composites.

(b-1) 15 wt. % graphite.

(b-2) 25 wt. % graphite.

(b-3) 45 wt. % graphite.



(b-4) 60 wt. % graphite.

(b) Higher magnification.

Figure 10. - Concluded.

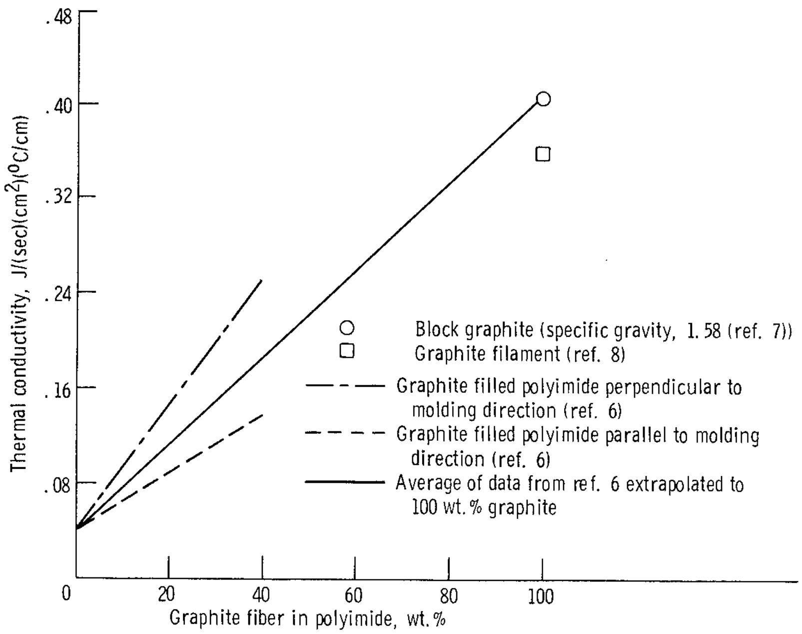


Figure 11. - Thermal conductivities of graphite, polyimide resin, and their composites.

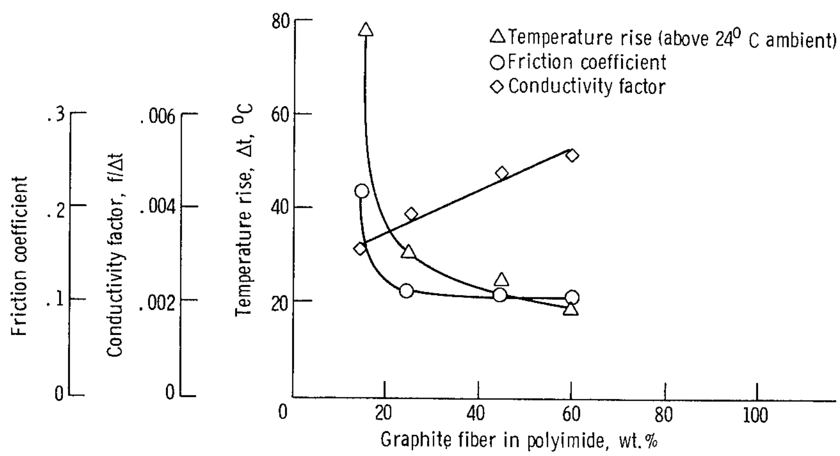


Figure 12. - Effect of graphite-fiber content on frictional heating. 24^0 C ambient temperature; radial unit load, 3.5×10^7 N/m^2 (5000 psi); journal oscillation in cylindrical bore at 1 hertz, $\pm15^0$.

Thermal conductivities were not calculated because of uncertainties especially in regard to the relative amounts of heat conducted away by the composite ball and by the metal shaft. However, the results at least qualitatively demonstrate the effectiveness of graphite fibers in improving heat dissipation from the sliding surface. This is of great practical significance especially with bearing materials containing polymers. For example, the commonly used design criterion for plastic bearings, which is termed limiting "PV" refers to the maximum product of unit load and velocity to which the bearing can be subjected before the surface temperature reaches the thermal degradation temperature of the polymer. Within the load carrying capacity dictated by mechanical strength considerations, improved thermal conductivity will therefore increase the limiting PV of the bearing material.

SUMMARY OF RESULTS

Experimental graphite-fiber-reinforced - polyimide composites were evaluated as self-lubricating materials for self-alining bearings. The composites were molded spherical elements with a cylindrical bore. The bearings were mounted with the journal free to oscillate in the cylindrical bearing bore; the spherical surface was primarily to impart self-alinement characteristics to the bearing. The outer race and journal were metal. Bearing tests were at unit loads to 3.5×10^7 N/m^2 (5000 psi); temperatures ranged from 24° to 340° C (75° to 650° F); and journal oscillation was at $\pm 15^\circ$ and 1 hertz. The principal results were as follows:

1. Low bearing torque and the best elevated temperature load carrying capacity of at least 3.5×10^7 N/m^2 (5000 psi) at 340° C (650° F) were obtained with a composite containing 45 wt.% graphite fibers. Friction coefficients were in the range of 0.08 to 0.13. The bearing was in good condition after 32 000 journal oscillations which were accumulated during one load capacity test and three temperature cycling tests in which the bearing was heated from room temperature to 340° C (650° F) followed by cooling to 66° C (150° F).

2. Friction coefficients tended to decrease with increasing graphite-fiber content. The lowest friction coefficients (0.05 to 0.10) were obtained with a composite containing 60 wt.% graphite, but the composite fractured at 340° C (650° F) and a unit load of 3.5×10^7 N/m^2 (5000 psi). This composition may therefore be suitable for application in which minimal bearing torque is essential and loads are not excessive.

3. The results strongly indicate that graphite-fiber - polyimide composites are promising candidate materials for low torque, sliding contact bearings at temperatures

up to 340° C (650° F). More detailed programs to develop reproducibly strong uniform composites and to more thoroughly defined bearing characteristics are in order.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 21, 1972,
502-31.

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